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Coastal Processes at Selected Shore Segments of South Baltic Sea and Gulf of Tonkin (South China Sea)

Rafał Ostrowski[1], Zbigniew Pruszak[1], Grzegorz Różyński[1], Marek Szmytkiewicz[1], Pham Van Ninh[2], Do Ngoc Quynh[2], Nguyen Thi Viet Lien[2]

[1]Institute of Hydro-Engineering of the Polish Academy of Sciences (IBW PAN), Kościerska 7, 80-328 Gdańsk, Poland, email: rafi@ibwpan.gda.pl
[2]Institute of Mechanics, Center for Marine Environment, Survey, Research and Consultation (CMESRC), 264 Doi Can, Hanoi, Vietnam

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Abstract

The paper presents a comparative analysis of physical processes occurring at two different coasts, which belong to two different geographic zones, namely a subtropical region exposed to monsoons and typhoons and a region of temperate climate with ice-snowy winter season. The former coast comprises sandy shores nearby Lubiatowo and the Hel Peninsula, located at the south Baltic Sea in Poland. The shore at Lubiatowo is relatively stable in the long run, while the shore along Hel Peninsula is mostly vulnerable to erosion and strongly protected by use of various measures (groins, seawall and artificial beach nourishment). The second site is the eroded (and partly protected by dikes) coast at Hai Hau in the Gulf of Tonkin (the South China Sea, Vietnam). This shore segment is built of mixtures of sandy and cohesive material, comprising both marine sands and river-borne sediments which nourish the coastal zone at the Red River mouth, located northwards of the Hai Hau beach. The present analysis is focused on differences and similarities of hydro- and morphodynamics between the above coastal zones in various time and spatial scales. The analysis shows that regional climatic and environmental conditions, associated with geographical zones, play a key role in dynamic evolution of the coastal regions and necessitate different engineering activities against erosion and flooding.

Key words: Non-tidal and tidal coast, waves and currents, sediment transport, morphodynamics

1. Introduction

All over the world, coastal regions are urbanized and inhabited by a significant part of the human population. Meanwile, climatic changes observed worldwide recent in years, have caused increased intensity of extreme phenomena, as well as destruction of sea shores and coastal infrastructure. Use and development of coasts for various purposes requires knowledge and awareness of natural phenomena occurring in such regions and of the forces governing these phenomena. Coastal physical processes are related to a number of factors affecting nearshore hydro- and morphodynamics. In non-tidal seas, the wind-wave climate, as well as the resulting wave-induced currents, are major driving forces of coastal evolution. In many regions, tidal water level changes and flows can also be of considerable importance for the coastal environment. It should be noted that various extreme events, like typhoons at the one site and seasonal ice-related phenomena at the other, can have a key influence on regional site-specific morphological behaviour, especially nearby river mouths and estuaries, see (Pruszak et al 2005a). Apart from local wind fields, the effect of nearshore waves depends on the local bathymetry and coastal topography. Wave propagation and transformation in the nearshore zone generate wave-driven flows and associated sediment fluxes that produce a specific response (change) of coastal morphology, see (Różyński et al 2001). The above processes are always mutually dependent and constitute a sophisticated system of highly nonlinear interactions. Therefore, their accurate theoretical description and modelling is troublesome and must be supported by extensive observations and measurements *in situ*.

In the Authors' opinion, the most important characteristics reflecting similarities and differences between coastal sites are:

- wind climate and exposure of a coast to wind fetch, conditioning energy of offshore wind waves. Frequency of appearance and duration of extreme events, like severe storms or typhoons, are of utmost importance,
- current structure including tidal flows and tidal rise of water surface, as well as storm surges,
- local geology, sources and sinks of sediment, type of sediment and grain size of sediments forming coasts as well as sea level and subsidence. Sediment represented by median grain diameters d_{50} implies vulnerability to erosion or accumulation,
- coastal morphology and proximity of large river mouths, in the form of deltas or estuaries. These features constitute specific conditions for wave transformation processes, including breaking of waves approaching the shoreline,
- temporary (seasonal) freezing of water at a shoreline causing, together with wind action, stacks of ice preventing coast from erosion. This process, greatly influencing shore behaviour during winter, is characteristic of many coastal regions located at higher latitudes, e.g. the Baltic Sea,
- level of human pressure and technical intervention into the natural coastal environment, for instance construction of harbour breakwaters which can often result in significant coastline changes, see e.g. (Szmytkiewicz et al 2000).

In order to assess how the above factors result in dissimilarities of coastal processes at two totally different regions, both geographically and climatologically, the present comparative analysis has been undertaken. The first site is located in central

Europe, and has a temperate climate, including periods with sea ice in winter, while the other is a subtropical region exposed to monsoons and typhoons (South-East Asia). The European study area lies in a semi-closed sea, namely in the South Baltic Sea (φ = 54°49.72′ N, λ = 17°49.67′ E), while the Asian site belongs to the coastal lowlands of the South China Sea, densely populated and highly sensitive to various cataclysms. These lowlands, partly depressive, lie in the Red River delta belonging to the Hai Hau District, Nam Dinh Province, (φ = 20°00′ N, λ = 106°25′ E). The Authors of the present paper are aware of difficulties surrounding the huge differences not only concerning geography and climate (temperate against tropical) but also differences in tides, river influence, sediment discharge (sinks and sources), as well as geographical development of the Baltic Sea and the coastal area of the Gulf of Tonkin, all of which makes the undertaken analysis a very challenging task. Therefore, the present study ought to be treated as an introduction drawing attention to the importance of geographical location and associated circumstances in specificity of coastal physical processes. This consciousness can be crucial for many decisions, e.g. concerning engineering measures regarding shore protection or choice of a proper computational model, suitable to local environmental conditions.

Main focus is on the fundamental hydrodynamic and morphodynamic features of the compared coastal regions. Because of recently observed climatic changes, the study has partly been devoted to flooding threats at both sites, related to the anticipated accelerated sea level rise. In this context, understanding of hydrodynamic and morphological patterns of these coastal regions is very important for coastal environmental protection and integrated coastal zone management, see (Pruszak and Zawadzka 2005).

2. Site Description

2.1. Site I – Baltic Sea (Non-Tidal Coast)

Site I is represented by sandy shores near to Lubiatowo and along the Hel Peninsula, located at the South Baltic Sea in Poland (see Fig. 1). This site is subject to continuous mild evolution due to the non tidal Baltic nearshore hydrodynamic impact (waves and wave-driven currents), including storm surges up to 1.5 m (the 100-year design water level). The deepwater maximum wave height can exceed $H_{\max} \approx 7$ m, while the significant wave height H_s can reach almost 4 m. While approaching the shore, waves are subject to multiple breaking over the bars. The wave period mostly varies from 3 to 8 s. The area is dominated by westerly and south-westerly winds, which are strongest in the autumn and winter. In this period, wind speed can exceed 25 m/s, while the long-term monthly averaged wind velocity amounts to about 6–8 m/s. The existing wind climate causes the wind-generated waves to be directed generally from the west to the east. These waves are subject to nearshore refraction and approach the coastline obliquely from the west sector. Consequently, the net longshore sediment transport is also directed eastwards. This transport has

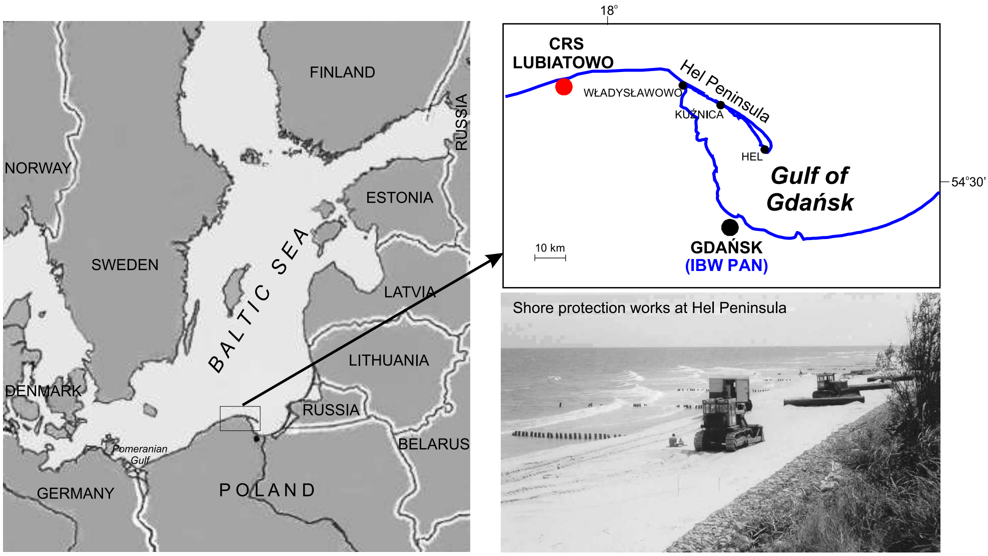

Fig. 1. Location of Site I (Lubiatowo beach and Hel Peninsula) in the South Baltic Sea

the highest rate in the surf zone, at water depth not exceeding approximately 4 m. As the net longshore sand movement is distinctly unidirectional, it causes problems in areas adjacent to Polish harbours, namely coastal erosion at lee sides (eastwards of the harbours) which compensates shore accretion westwards of the harbours structures).

The coasts of Lubiatowo and the Hel Peninsula are similarly exposed to storms from the north and north-east. The shore at Lubiatowo also experiences storms from the west and north-west, while the shore of the Hel Peninsula is additionally open for storm waves coming from the east. Due to these similarities, both shore segments can be treated as typical representative south Baltic coasts. In the last century, long-term sea-level rise (SLR), resulting from the superposition of geological, meteorological, and other factors, showed 15–20 cm/100 year, depending on the location along Polish south Baltic coast (Pruszak and Zawadzka 2005). At the same time, subsidence of the seabed in the South Baltic is very slow (lower than 1 mm/year) and decelerates continuously (Zawadzka 1999).

The sediment forming the beach and the foreshore is non-cohesive, with a predominance of sand with sediment diameter oscillating about the average value of d_{50} = 0.22 mm. The Polish south Baltic coastal profile is typically characterised by a few nearshore bars. The number of bars depends on the location. Distinctly accumulative or stable coastal segments display cross-shore profiles with 3–5 bars while there are not more than 1–2 bars at eroding shores. The characteristic cross-shore transects measured at Lubiatowo and at Hel Peninsula are plotted in Fig. 2. The shore at Lubiatowo is relatively stable in the long run, while the shore of the Hel Peninsula is vulnerable to erosion, and several measures have been taken to protect

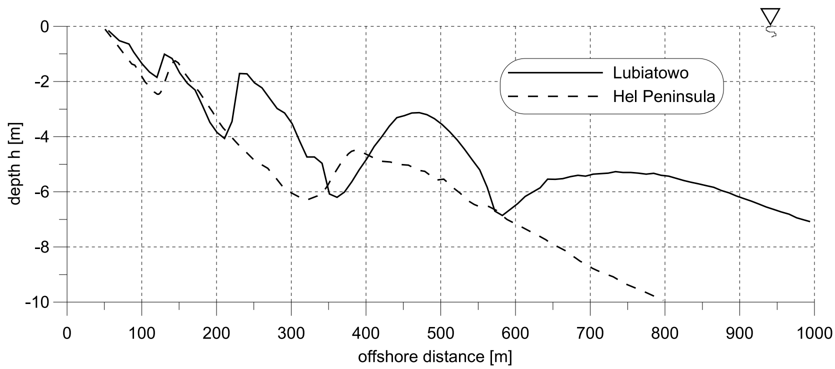

Fig. 2. Multi-bar Baltic cross-shore transects at Lubiatowo and Hel Peninsula

the coast. The net longshore sediment transport is directed eastwards, at a rate of about $80 - 100 \times 10^3$ m^3/year nearby Lubiatowo and slightly more than 100×10^3 m^3/year along the Hel Peninsula. Spatial variability of net sediment transport rates, which directly depend on nearshore hydrodynamic processes, are responsible for coastal morphodynamics.

Climate conditions are greatly influenced by moist air currents from the Atlantic Ocean, as well as by dry continental air from Eastern Europe. Considerable differences between summer and winter temperatures characterise the coastal climate of the South Baltic. The mean air temperature is about +7.5°C and varies from −2°C in February to +16.5°C in July. Mean monthly water temperature varies from +1.2°C in February to +17.8°C in August. Ice at the shoreline is present for about 20 days/yr (usually from the end of January to the end of February). Water salinity amounts to about 7.5 PSU. The vegetation period lasts about 200 days, usually from the beginning of April till early November. The majority of precipitation, amounting to 650–690 mm/yr, is discharged in summer and autumn. Usually, there are 130 rainy days a year, and the snow cover lasts about 34 days.

The formation and character of Polish shores are generically associated with the last glacial period and phases of development of the southern Baltic Sea. The coastal sections composed of Pleistocene sediments form sandy beaches with dunes and cliffs. The coast at Lubiatowo, with its wide beach and wood-overgrown dunes, is practically an uninhabited area (see Fig. 3). However, in the summer season (particularly in July and August), this region is visited by thousands of tourists who are offered accommodation in the village located 2 km landwards and at a camp site or bungalows situated 200–300 m from the shoreline. In 1970, the IBW PAN Coastal Research Station (CRS) was established on this coast. The CRS's activities are related to observations of meteorological, hydrological, hydrodynamic and morphodynamic phenomena occurring in the Baltic coastal zone. Numerous field campaigns at CRS Lubiatowo have been focused on registration of deep and shallow water wave processes, nearshore currents, sediment transport and short-term a)

b)

Fig. 3. Lubiatowo site: a) top view, b) ice phenomena on the shore

coastal morphodynamics. Within routine measurements, wind conditions at the laboratory are recorded continuously. Besides, long-term variability of dune and beach morphology is monitored regularly every month. Sea bottom topography in the nearshore zone area covering an area of 2.6 km in the alongshore direction and about 1 km in the offshore direction is measured a few times per year.

The Hel Peninsula, with the harbour of Władysławowo located at its root, is an example of an area with a few mutually related coastal zone management/engineering problems, namely shore erosion, silting-up of the waterway and the harbour entrance, as well as instability of the main breakwater. The region is dominated by eastwardly directed longshore sediment transport (as at most of the coastal segments in Poland, see e.g. (Larson et al 1999). After construction of

Władysławowo harbour the longshore transport was totally interrupted by breakwaters, the presence of which triggered distinct accumulation westwards and erosion eastwards of the harbour. On the west side, the impact of the harbour displaced the shoreline more than 300 m offshore in comparison to the original location. Because of erosion eastwards of the harbour, a lot of groins were built. At present, the stretch of the shore protected by groins stretches to Kuźnica, a village located 12 km from the root of the peninsula, which corresponds to about 1/3 of its length (see Fig. 1). Artificial nourishment of the Peninsula, which was started at the end of the 1970's, together with existing groins, is the main measure protecting the shore in this region. In 1989–1998 the open shore of the Peninsula was nourished with 8.8 million m^3 of sand in total.

It should be noted that the Hel Peninsula was eroded even before the construction of Władysławowo harbour. Intensification of this process in the first half of 20th century was probably caused by extension of protection systems against erosion at coastal segments westwards of Hel Peninsula, which in turn resulted in reduction of the supply of sandy material at the peninsula.

Coastal erosion rate at the Hel Peninsula depends mostly on number of stormy days during which the raised sea level causes submergence of the beach and abrasion of dunes. Data collected by IMGW (Institute of Meteorology and Water Management) implies that since 1970 the frequency of storm surges has increased considerably, e.g.:

- in the period 1951–1960 storm surges higher than 0.7 m occurred 12 times;
- in the period 1961–1970 storm surges higher than 0.7 m occurred 11 times;
- in the period 1971–1980 storm surges higher than 0.7 m occurred 21 times;
- in the period 1981–1990 storm surges higher than 0.7 m occurred 38 times.

Local big depths (trenches) situated obliquely to the coastline are said to constitute an additional reason for erosive processes as more wave energy reaches the shore in these places.

2.2. Site II – South China Sea Tidal Coast

The second coast represents the eroded (and partly protected by dikes) Vietnamese beach of Hai Hau, located in the Red River Delta area – Gulf of Tonkin of the South China Sea, as shown in Fig. 4. This site is subject to rapid changes, as described e.g. by (Vinh et al 1997) and (Zeidler and Nhuan 1998), induced by factors and forces typical for sub-tropical zones, see (The East Sea Monograph 2003, Ninh et al 1991 and Quynh et al 1998), related mostly to winter and summer monsoons, typhoons, strong tidal currents and occurrence of heterogeneous fine material, containing numerous organic additives. It is worth noting that the geological subsidence in Vietnam is limited to less than 3 mm/year in the deltas and less than 1 mm/year along the central coast.

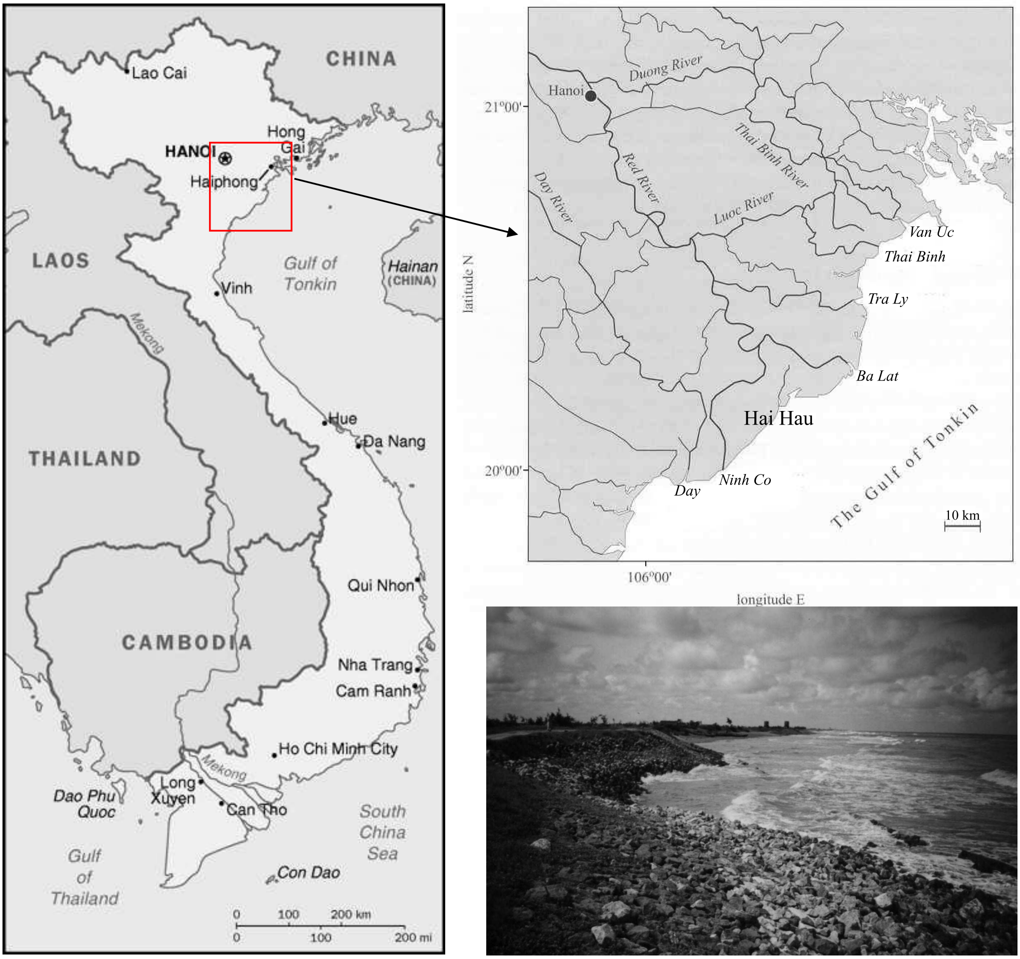

Fig. 4. Location of Site II (Hai Hau beach) in the Gulf of Tonkin, the South China Sea

The Hai Hau beach is a part of the Red River delta coast, lying between the Ba Lat mouth in the north and the Ninh Co outlet in the south. The middle part of this coastal segment is subject to very intensive erosion, which necessitates protection of the most threatened and valuable land areas. To this end, numerous dikes are constructed along the shoreline at the Hai Hau beach.

The shoreline at Hai Hau is NE-SW oriented, coinciding with the main predominant northeast monsoon and associated wave direction. Theoretically, wind from N-NE cannot generate intensive wave motion. However, relatively high waves are induced by the wind from this sector and that approaching the Hai Hau beach, since waves diffract around the Ba Lat. Analysis of statistical data collected over 100 years (1891–1990) shows an evident increase in the influence of tropical cyclones in Vietnam. Typhoons and violent storms strike the coast of Vietnam every year causing high rainfall, extreme wind speeds, high waves and storm surges. The northern provinces encounter the majority of typhoon events. Among those occurring throughout the 37 years between 1954 and 1990, 31 typhoons of grade 10–12 in the Beaufort scale were observed. The annual average number of typhoons is 4.7, but in several years (1964, 1973, 1989) there were more than 10 and in other years (1976) none was observed (Ngu and Hieu 1991) or (Mao 1992). The number seems to have increased particularly over the last 2 or 3 decades and there has been rise in distinct typhoons over the northern part of central Vietnam. Also, a tendency towards longer durations of individual extreme events was noticed. In the last decades, one of the biggest typhoons which had ever struck the coast of North Vietnam, hit the coast of the Nam Ha and Thai Binh Provinces on 23rd Oct. 1988 (typhoon name – Pat). The maximum wind velocity of this event was V = 35 m/s, whereas the associated tidal level reached 205 cm and the mean wave height 2.0 m (Hon Dau Station). Another major typhoon occurred on 12th Jun. 1989 (typhoon name – Dot). Exemplary trajectories of typhoons between 1986 and 1990 are presented in Fig. 5 (Lien et al 2005).

Field observations show that the tides (astronomical tides neglecting meteorological effects) are of regular diurnal type, with height of 2.0–2.5 m. The predominant diurnal tidal flow has a velocity of 25–40 cm/s, and the predominant direction in the coastal area is NE (tide rising) and SW (tide ebbs). The maximal tidal velocity reaches the value of 60–80 cm/s. The tidal currents are among factors having a considerable role in the formation of the tidal flats and tidal channels in the coastal low wetland area. At the Hai Hau coast tidal waves propagates from south to north resulting in a north-easterly directed flood current and a south-westerly directed ebb current. The open sea area is subjected to the influence of northerly and north-easterly winds in winter, and easterly and south-easterly winds in summer. Those winds control the wave regimes in this area (with predominant winds from northeast, east and southeast directions). Due to the openness of the sea surface and relatively long wind duration, the waves are strongly dependent on wind conditions. The easterly waves move obliquely to the coast and thus in the case of N-E (winter) and S-E (summer) wave approaches one can expect relatively strong longshore currents. According to 30 years of wind measurements (1949–1988) and wave observation at Hon Dau station, the estimated average wave height is in the range of 1.2–1.4 m (summer) and about 2 m (winter) offshore and 0.8–1.2 m near the shore, the maximal wave height changes from 6.0–8.0 m in open sea to 3.0–5.0 m in the nearshore. Rough estimation of monthly maximum wave height occurring in the period 1986–1993 at the same station shows changes from 2.1 m, SE direction (April) with 4.2 m, SW in July to 9.7 m, E direction (October) (VVA Report – A8 1995). Due to a very gentle coastal slope $s \approx 0.0012 - 0.004$, the long distance over which wave transformation and energy dissipation is observed creates a relatively wide breaker zone. Hence, theoretically, only severe storms or typhoons accompanied simultaneously by high water level (e.g. tide rising) create the dangerous

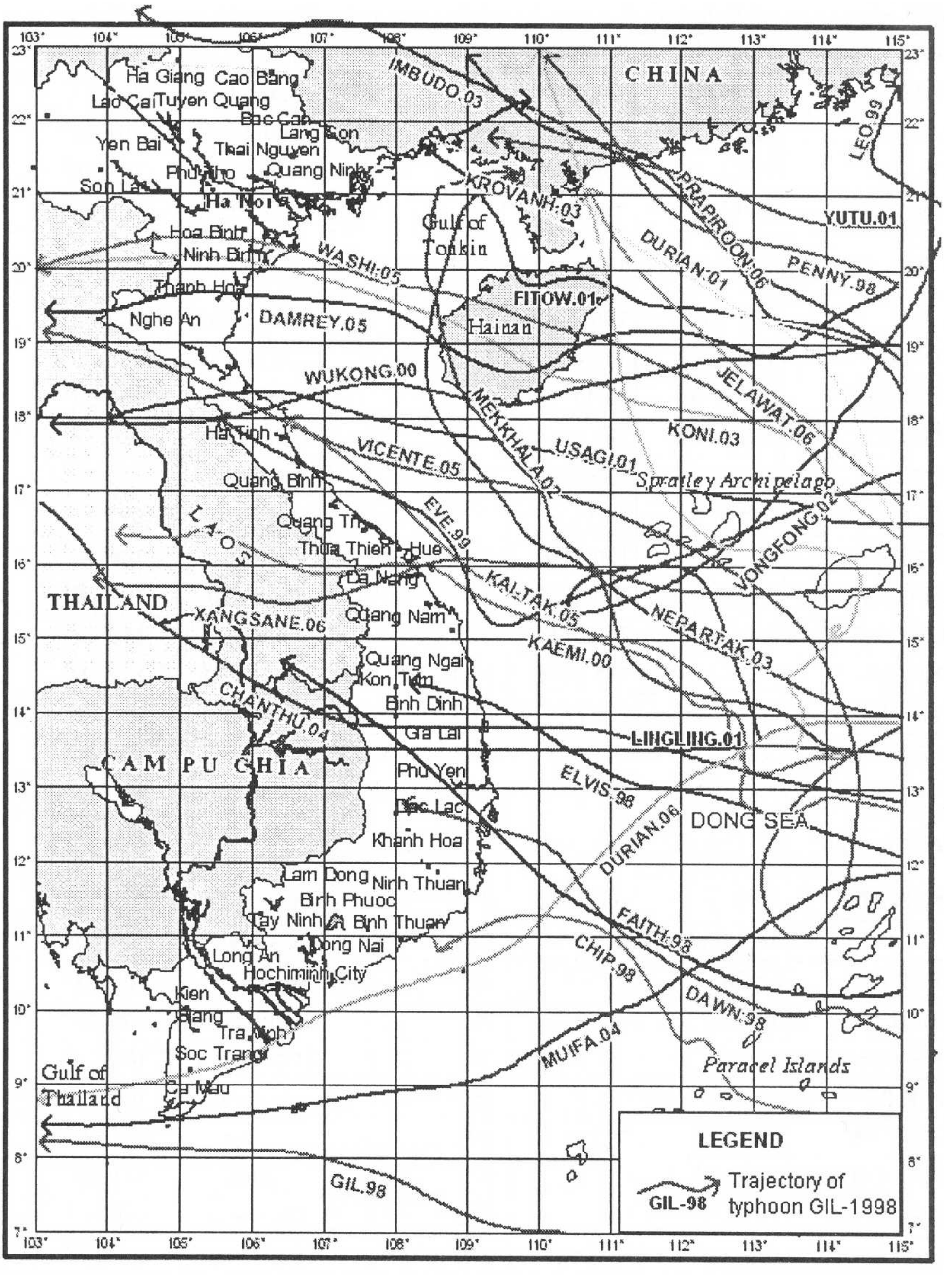

Fig. 5. Typhoon trajectories in 1986–1990, after Lien et al (2005)

conditions for this kind of beach (structures). The wave period changes from 7 to 10 s. Typhoons are normally accompanied by storm surges. Half of the recorded typhoons caused storm surge over 1 m high and 11% over 2.5 m, (Tu Mao 1992) or (VVA Report – A8 1995). Aside from the short-term storm surges, a long-term sea level rise has been observed. In the last century, the average rate of sea level rise (registered in the period from 1957 to 1990) was 2.24 mm/yr.

The net annual littoral current, due to the prevailing influence of winter monsoons is directed southwards. In the deeper part of the coastal zone, ocean currents occur. In the summer time, down-welling and clockwise circulation is observed. In winter, the reverse situation takes place. Thus the flows have northward direction in summer and a southward one in winter. The ocean current velocity in both cases is not high, varying from 10 to 25 cm/s.

In most parts of North Vietnam, the coasts present young alluvial muddy bodies nourished by river sediment. They need continuous river supply to compensate for fine material washing by waves and currents. Sand exchange between the muddy coasts and the surrounding areas is negligible. Young alluvial sediments are subject to compression, which causes bottom subsidence. This process has a rate of not more than 3 mm/yr. Sandy coasts, where they exist, consist of fine, medium and coarse quartz sand. The superficial sediments in the study area have grain size d, varying from 0.25 to 0.001 mm. The sediments considered as the coarsest have $d = 0.14$ mm. Most of this sediment occurs in the surf zone and is distributed mainly along the shoreline in the form of bars, ridges and dunes. For the area of the Hai Hau District, mean sediment diameter is around $d = 0.09$ mm. A current with the velocity of 0.3 m/s is enough to pick up a sediment particle of 0.11–0.12 mm from the bed and transport it away. This means that the sediment is very mobile. The bottom slope is rather gently inclined offshore (see Fig. 6), which results from fine sediments building the sea bed and abrasion of the shore. The shoreline retreats continually and the eroded material is deposited in the nearshore zone, constituting the mild slope (smaller than 0.01). The erosion rate amounts to about 10 m per year on average (with the existing sea dike system). Although the dikes are rebuilt systematically, one line of the dike system is subject to total destruction within a few years (the most solid dikes can resist wave impact for 20–30 years at maximum). The total amount of sediments discharged by the Red River mouth to the sea is assessed from about 75 million ton/year to values exceeding 100 million ton/year. This sediment transport is distributed irregularly over the year, with 91.5% of annual volume in the flood season and 8.5% in the dry one. This sediment load is composed of 11.6% sand, 59.2% aleuritic and 13% clayey material.

Along many coastal segments in Vietnam, dikes have a crucial function in protecting low-lying areas against flooding. Sea dikes, with some segments having seaward slopes covered by solid revetments, play a predominant role concerning shoreline defence against erosion in the Hai Hau district. Construction of new dike systems and the upgrading of old ones is a continual process. At one of

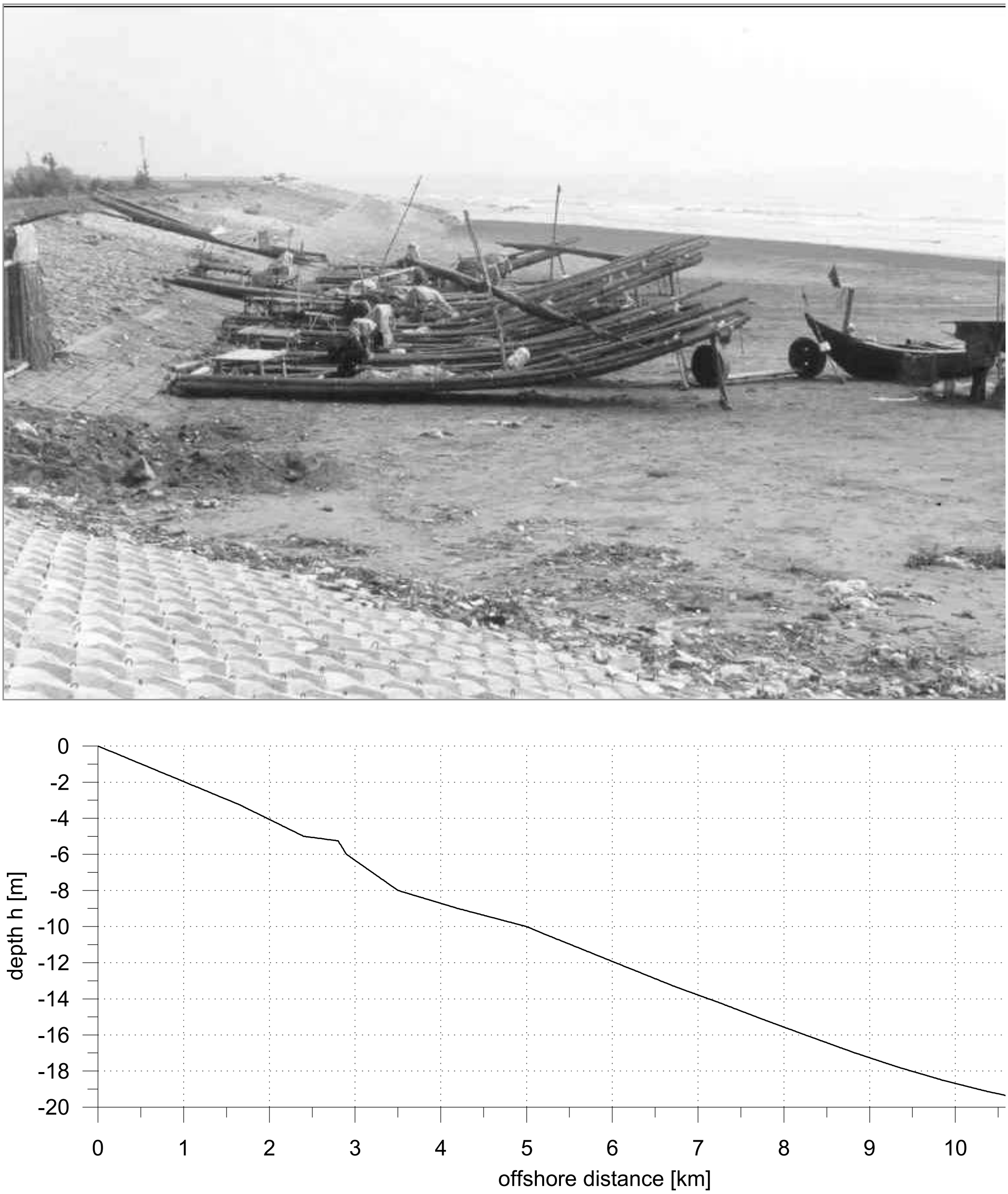

Fig. 6. Typical look and cross-shore profile of Hai Hau beach

the most intensively eroded coastal segments in the Hai Hau district, the average annual coastline retreat has resulted in a destroyed dike line every 10 years. Dike maintenance costs are very high and in the Hai Hau district (75% of the Hai Hau coastline is retreating) they represent nearly 70% of the total sea defence budget. The dikes are fundamentally constructed to withstand concurrent design events. In general the dikes are under-designed (crest too low) to protect against accelerated sea level rise.

3. Field Data and Analysis

The present comparative analysis of the two considered sites was based on available data which had been collected within numerous field experiments and surveys. The data mostly comes from recent field measurements which were carried out at CRS Lubiatowo in 2003 and 2006, as well as on the coast of Hai Hau in the period 2002–2005.

3.1. Hydro-Meteorological Conditions and Nearshore Processes

3.1.1. Site I

In the Baltic non-tidal coastal zone, waves are the main driving force of nearshore hydrodynamic processes, which comprise currents generated during wave transformation (including wave breaking). The offshore waves are induced by the wind field over the entire Baltic Sea and therefore the local wind conditions cannot be treated as a fully reliable indicator for the local wave conditions. The local wind speed and direction, however, can still be used as an approximate measure. The maximum velocity of wind gusts ever recorded at CRS Lubiatowo attained 35–40 m/s, while the average wind speed over 10 minutes has never exceeded 20 m/s. During a several month long field experiment in 2006, the maximum wind speed amounted to 28 m/s while the mean speed did not exceed 12 m/s. The wind blew predominantly from the west and the north-west. Wind characteristics at the Hel Peninsula are very similar to the abovementioned.

The most recent extensive field experiment at CRS Lubiatowo of 2006 lasted from September to December. The location of measuring equipment is depicted in Fig. 7. Continuous registrations of deep-water waves were carried out by use of a Directional Waverider Buoy anchored at a depth of 15 m, about 1850 m offshore (54°49.72′ N, 17°49.67′ E). Records were taken every hour with a sampling frequency of 3.84 Hz.

To characterise wave climate, the following representative wave parameters are selected: significant wave height H_s, root-mean-square wave height $H_{rms} = \left[1/N \sum (H_i)^2\right]^{1/2}$, mean wave height $H_{mean} = 1/N \sum (H_i)$ and maximum individual wave height $H_{\max} = \max(H_i)$. The results of measurements in the period from 19 Sep. to 30 Nov. 2006 are plotted in Fig. 8.

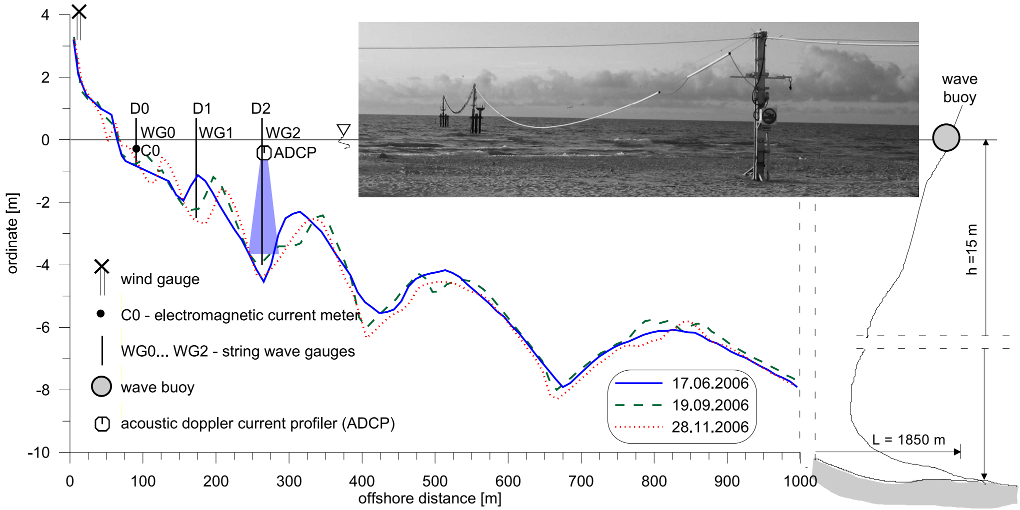

Fig. 7. Measuring devices and cross-shore profile during field experiment Lubiatowo 2006

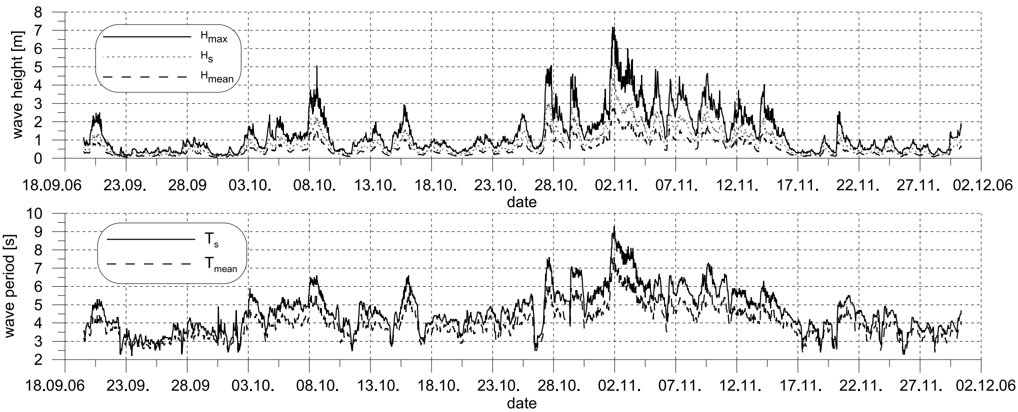

Fig. 8. Offshore wave heights and periods registered at CRS Lubiatowo from 19 Sep. to 30 Nov. 2006

The largest significant offshore wave height amounted to $(H_s)_{max}$ = 4.66 m, while the maximum value attained H_{max} = 7.18 m (end of October – beginning of November 2006). The mean wave height averaged over the entire period was equal to $(H_{mean})_{mean} \approx 0.71$ m. The mean wave period T_{mean} was in the range from 3 to 7.5 s (most often 4–5 s). During the heaviest storm, the significant wave period T_s slightly exceeded 9 s. The characteristic parameters of deep-water waves registered in the period from 19 Sep. to 31 Dec. 2006 are summarised in Table 1.

The offshore wave height exceedance curve for the period from September to December 2006 is plotted in Fig. 9. In addition, analogous older curves are given, corresponding to the period from October 1996 to February 1997 and from January

Table 1. Characteristic deep-water (h = 15 m) wave parameters at CRS Lubiatowo in the period from 19 Sep. to 31 Dec. 2006

Month	$H_{\max}$ [m]	$(H_s)_{\max}$ [m]	$(H_s)_{mean}$ [m]	$(H_{mean})_{\max}$ [m]	$(H_{mean})_{mean}$ [m]	$(H_{rms})_{\max}$ [m]	$(H_{rms})_{mean}$ [m]	$(T_s)_{mean}$ [s]	T_{mean} [s]
Sep.	2.50	1.38	0.38	0.90	0.25	0.99	0.28	3.65	3.23
Oct.	5.09	3.08	0.87	1.99	0.57	2.21	0.63	4.86	4.10
Nov.	**7.18**	**4.66**	1.23	3.00	0.80	3.90	0.88	5.28	4.43
Dec.	5.61	3.35	1.17	2.18	0.76	2.41	0.84	5.25	4.37

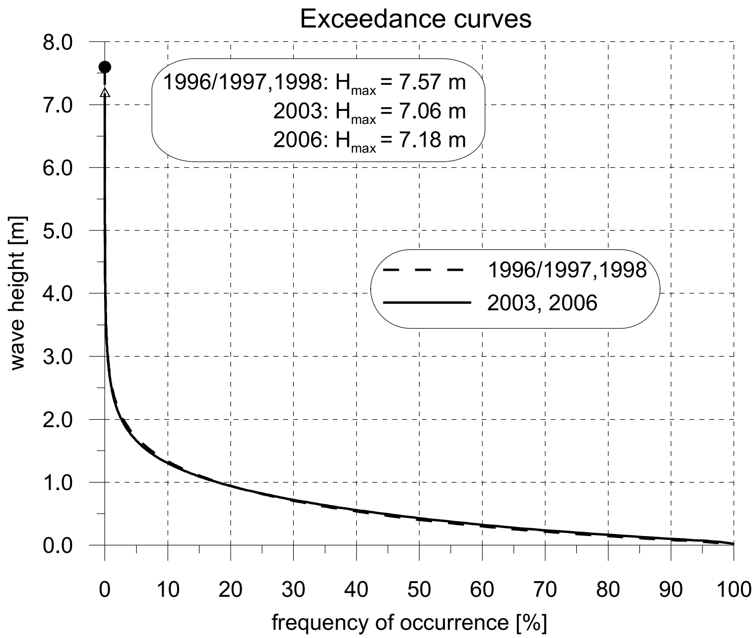

Fig. 9. Experimental deep-water wave height exceedance curves for CRS Lubiatowo

to October 1998, as well as from autumn 2003 (the latter one is almost identical to the one of 2006). The comparison of all these curves shows that no distinct change in the regional deep-water wave climate took place between the periods of observation.

The field experiment Lubiatowo 2006 also comprised measurements of nearshore (transformed and broken) waves at locations D0, D1 and D2 (see Fig. 7). An example of a wave record in the nearshore zone, at the water depth of $h = 4.4$ m (location D2), is given in Fig. 10. It can be seen that the biggest wave heights at this point did not exceed $H_{\max}$ = 2.6 m because of previous wave energy dissipation due to breaking on the nearshore sloped seabed.

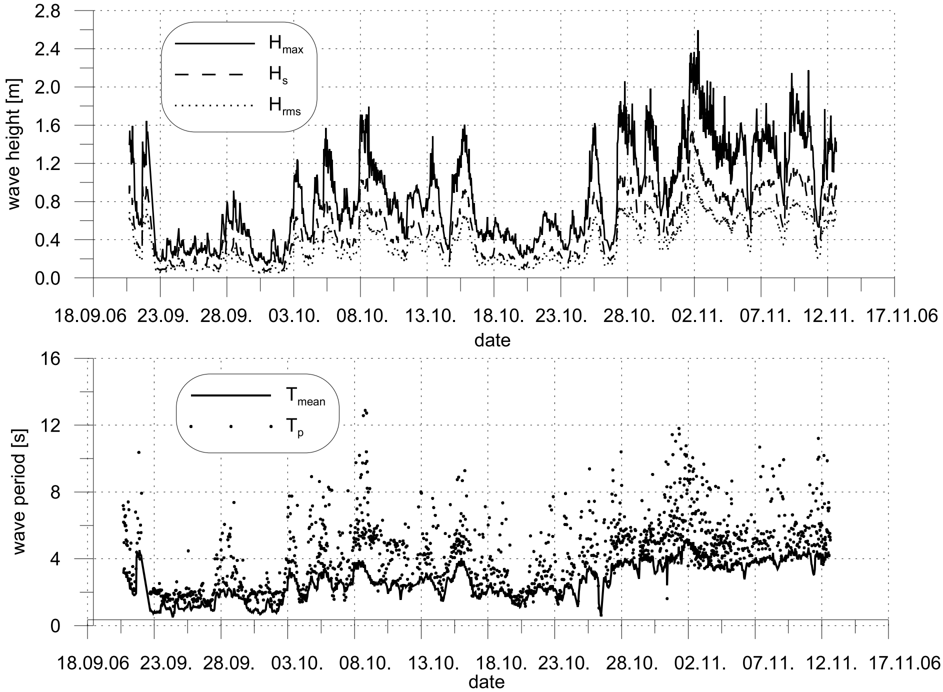

Fig. 10. Shallow-water (h = 4.4 m, location D2) wave heights and periods registered at CRS Lubiatowo in autumn 2006

In the non-tidal Baltic Sea, the recorded short-term sea level rise can only be explained by storm surges. The most extreme storm surge observed on the south Baltic coast resulted in a sea level rise of 1.83 m above the mean level. An increase of 1.3–1.5 m above mean can occur every year during autumn and winter, when strong winds cause high storm surges in the region.

Measurements of coastal currents at CRS Lubiatowo have been carried out for more than 20 years. Large amounts of data show that the cross-shore velocities are distinctly higher in the nearbed layers of water column in comparison to its middle part, while the vertical distributions of longshore velocities are more uniform. The cross-shore flows are mostly directed seawards (as they compensate a wave drift directed onshore) and their velocities rarely exceed 0.3–0.4 m/s. The longshore currents at the south Baltic coast are more intensive, having time-averaged velocities reaching 1.2 m/s during storms with waves approaching the shore obliquely. These features were confirmed during the field campaign of 2006. The records of coastal currents registered at location D2 (water depth of h = 4.4 m) in Lubiatowo during the field campaign of 2006 are presented in Fig. 11. It should be noted that the overall analysis of flow velocities on the entire cross-shore profile at Lubiatowo reveals a considerable impact of the multi-bar profile. It causes multiple wave breakings and development of wave-driven return flows.

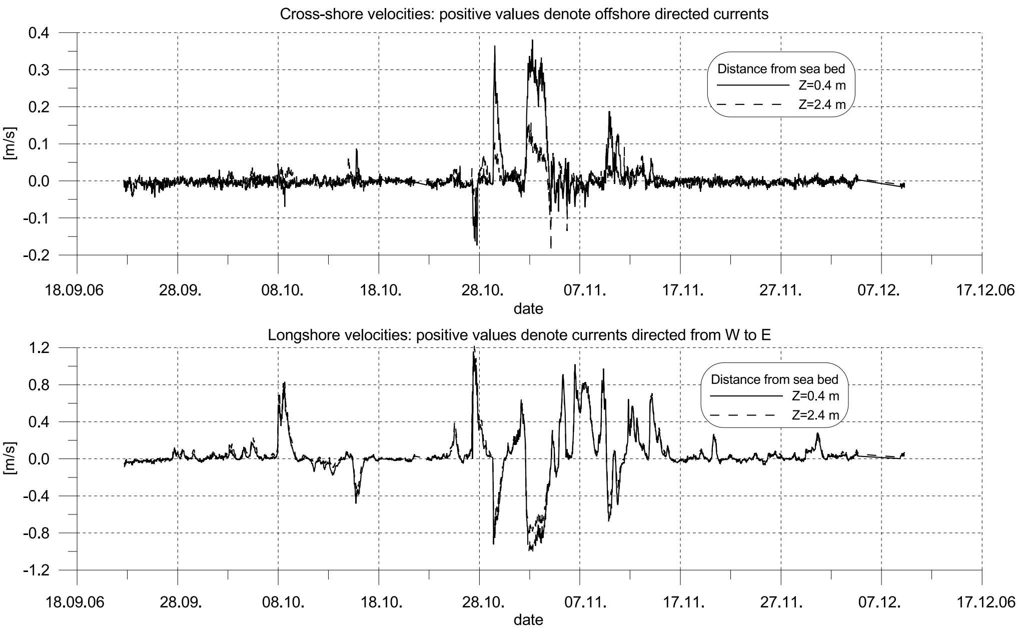

Fig. 11. Velocities of coastal currents registered at location D2 (water depth of h = 4.4 m) in Lubiatowo during field campaign of 2006

3.1.2. Site II

The wind climate in north Vietnam is distinctly composed of two monsoons, the dynamics of which is dependent on seasonal variability. The winter monsoon (from November to March) is characterised by strong winds blowing from the north and lower precipitation, while the summer monsoon is characterised by moderate winds blowing from the south and higher precipitation. Additionally, there is a transition period between two main monsoons (April and October), characterised by light eastern winds.

Perhaps the most important factor shaping coastal evolution in Vietnam, is typhoons. Recent analyses indicate the importance of growing storminess, manifested by a slight magnification of typhoon peak power and their considerable longer duration in recent decades. Fig. 12 illustrates the growth of maximum typhoon power in the form of extreme value probability distribution function of (peak) wind velocity at the centre of the typhoons, plotted for the perods 1960–1982 and 1982–2000. For example, from this plot we can judge that 90% of peak wind velocity in the earlier period was less than 145 knots, whereas for the later period 90% threshold was 162 knots (83 m/s). Fig. 13 is much more convincing, as it presents extreme value probability distribution functions for the duration of winds greater than 120 knots (62 m/s) for the same two periods. We can see that in the earlier period 90% threshold was about 40 hours and in the later period it almost doubles to 70 hours.

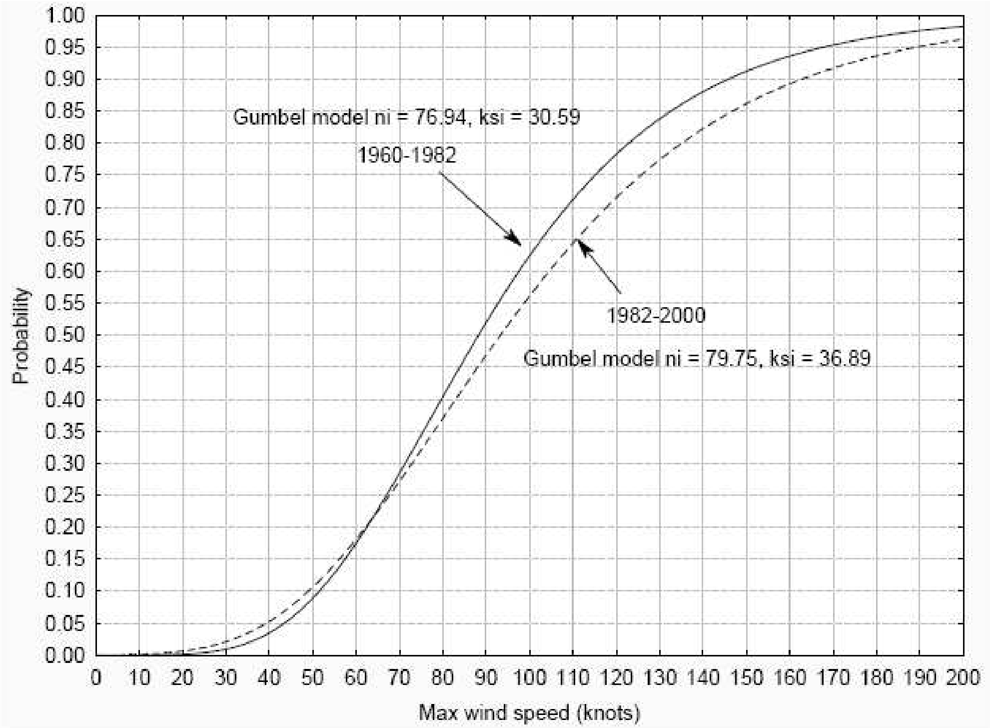

Fig. 12. Increasing peak wind velocity

These results show that the Vietnamese coast will be experiencing substantially greater extreme loads and therefore will be facing serious threats of accelerated erosion. Mitigation of such processes will therefore have to become a prerequisite of any coastal zone management scenario and policy.

Tropical cyclones (typhoons) in Vietnam can generate wind speed attaining a mean value of 35 m/s. During such events, the wind gusts much exceed 50 m/s.

As a result of the wind climate, the deep-water wave regime in the Gulf of Tonkin displays seasonal features. Observations at Hon Dau station, (Pruszak et al 2002) have shown that the deep-water waves from NE predominate in winter, whereas in summer, the offshore waves come mainly from SE. The estimated average height of deep-water offshore waves lies in the range 1.8–2.0 m for winter and 1.2–1.4 for summer, see (The East Sea Monograph 2003).

According to van Maren (2005), winds in the Gulf of Tonkin give rise to smaller waves than reported above, i.e. having a significant wave height H_s of about 1.4 m during the dry season (winter) and below 1 m during the wet season (summer). Further, van Maren (2005) reports that heavy typhoons in the north part of the Gulf

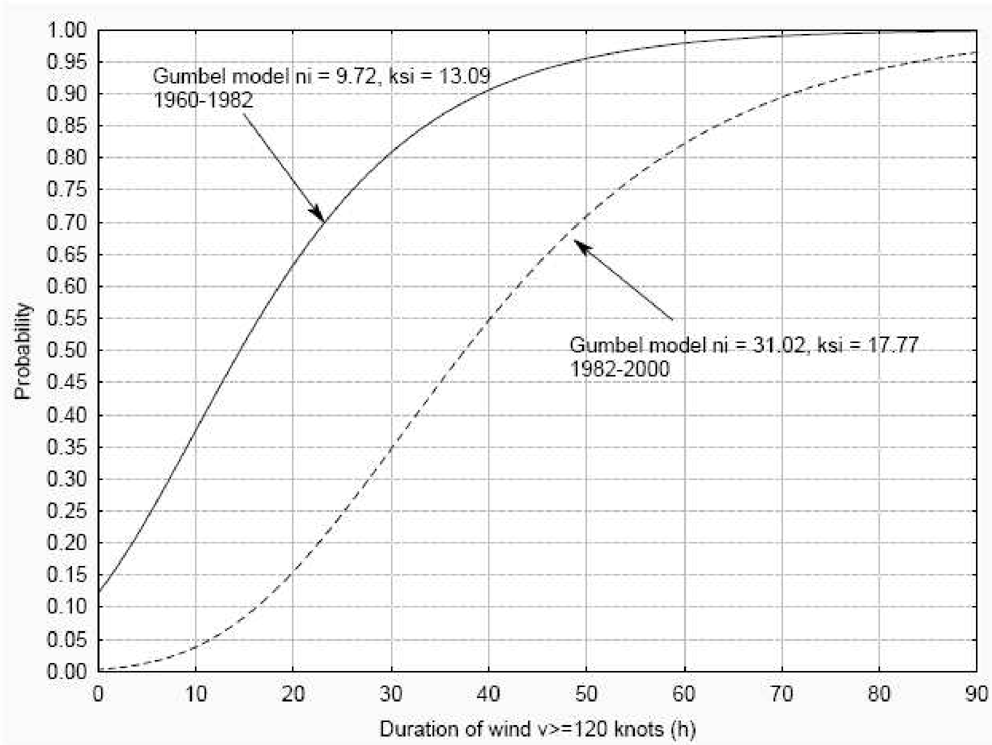

Fig. 13. Increasing duration of peak wind velocities

of Tonkin generate waves with H_s attaining 6 m, accompanied by storm surges up to 3 m.

No long-term wave data is available for the Hai Hau beach. In 2005 and 2006, four short-term field campaigns were organised around the Hai Hau beach. All the measurements were carried out, however, in moderate weather conditions. The wave records taken by a station at the depth of 20 m have shown that the significant wave height H_s exceeds 1 m during 10% of the measurement time in winter, while H_s exceeds 0.6 m during 10% of the measurement time in summer.

The major currents in the coastal zone adjacent to the Hai Hau beach comprise wave-driven, tidal and wind-induced currents, as well as river outflows (near the river mouths only). The wave-driven currents are found to be the main factor generating sediment transport, while the tidal currents probably play a primary role in the formation of tidal flats and tidal channels in the coastal low-lying wetland areas, unprotected from flooding and erosion, see (Quynh et al 2006). The average tidal flow in the nearshore zone has a velocity of 0.25–0.40 m/s, while the maximum velocity can reach 0.6–0.8 m/s.

3.2. Sediment Transport and Morphodynamics

3.2.1. Site I

The shore at two analysed south Baltic regions, as shown in section 2, is characterised by a gentle slope (having an inclination of about 1–1.5%). At Lubiatowo coast the shore is relatively stable, although a very gentle erosive tendency has been observed over recent years. The mean beach width lies between 15 and 70 m. It is bounded by dunes and featured by multi-bar cross-shore profiles, which usually show 4 stable bars (see Fig. 7) plus the ephemeral one, near the shoreline. This bar interacts with the shoreline supplying or removing the sediment and simultaneously protecting the shore from wave action. In extreme storm or long calm periods, this bar seldom exists. In stormy conditions it is washed away by moving the material offshore, and during quiet periods it moves onshore until it arrives on the shoreline. This causes the beach build-up and berm formation. The second Baltic beach site (Hel Peninsula), despite the distinct sand deficit and domination of erosion, has many features similar to the ones at Lubiatowo: the cross-shore profile has bars, the sea bed is built of pure sand with the median grain size d_{50} = 0.18–0.20 mm, slightly finer than the sand nearby Lubiatowo. The shoreline evolution can be determined from long-term observations. Such surveys have been carried out regularly (every month) at CRS Lubiatowo along a 2.6 km shore segment since 1983. The results of these measurements show that short-term (annual) changes of the shoreline position (in the case of long-term equilibrium) have never exceeded 25 m. It should be noted that each local erosive process is compensated by accumulation in adjacent areas. Thus, the entire observed coast is stable in the long run. Although no distinct erosive or accumulative trends exist, local long-term displacements of the shoreline reach 80–90 m (see Fig. 14). At Hel Peninsula (where shoreline evolution is presently controlled by periodic beach fills) the respective quantities have never exceeded 50 m since 1989. Before, local shoreline retreats 3–4 km eastwards of Władysławowo amounted to 100 m and even more. Recently, coastal morphological features are said to be shaped not only by the wind-driven waves and currents, but also by some secondary effects associated to infragravity waves, like edge waves, see (Pruszak et al 2005b). These oscillations are presumably the main factor causing appearance of specific rhythmic shoreline forms (various-scale beach cusps). Self-regulation beach processes are the second important factor responsible for generation of rhythmic shoreline forms in a dissipative (multi-bar) coastal system.

3.2.2. Site II

Due to the fact that the offshore wave energy in winter (coming from the north) is much greater than that in summer (coming from the south), the southward sediment transport, encompassing about 70% of the gross transport, is much higher than the northward sediment transport, constituting only about 30% of the gross transport,

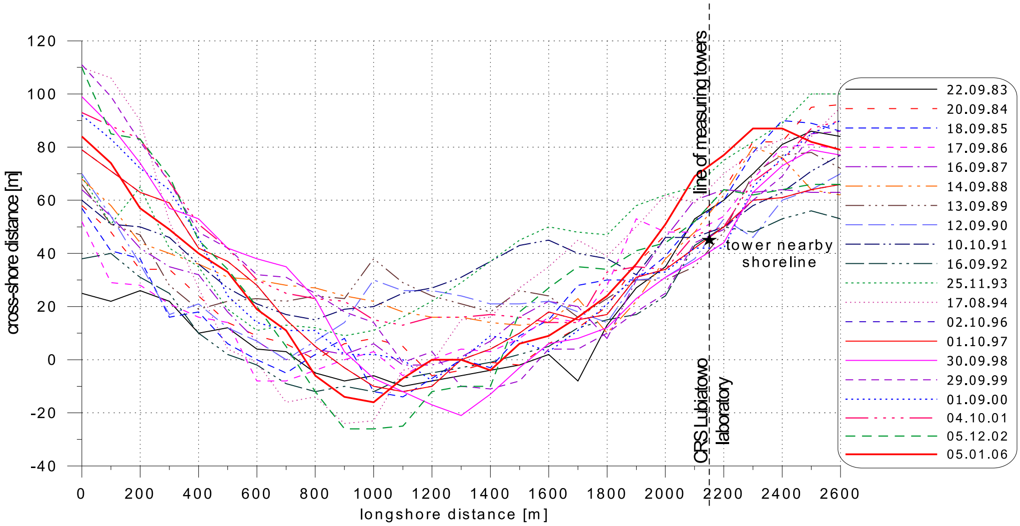

Fig. 14. Long-term shoreline evolution nearby CRS Lubiatowo: selected annual shoreline positions in 1983–2006

which results in a large net sediment transport to the south. Also, spatial variability in the longshore sediment transport rates to the south (in winter) are higher than in the transport to the north (in summer). Therefore, independently of the cross-shore transport, there is a significant part of fine sediment being moved into deep water by longshore transport during winter. This denotes that the serious erosion at Hai Hau beach mainly occurs during winter periods.

As evidenced in previous studies, see e.g. (Pruszak et al 2002), river outflow as well as riverine sediment from the Red River seldom reaches the Hai Hau coastline. The sediment from the Red River is mainly deposited within a 10-km area around the river mouth, while some amount of finer sediment is transported to deeper water. Thus, the coastline of Hai Hau beach is poorly supplied with sediment from the Red River. This is expected to contribute to the sediment deficit and associated erosion along the Hai Hau coastline. Presumably, the headland of the Ba Lat mouth produces significant diffractive and refractive effects on the waves approaching from the north, resulting in an alongshore variation of wave heights and angles in the coastal zone of the Hai Hau beach. This, in turn, is a reason for a spatial variability of longshore sediment transport rates. In particular, increasing net annual longshore sediment transport rates southwards of the Ba Lat mouth causes serious erosion at the Hai Hau coastline, see Fig. 15. In recent decades, the erosion rate is lowered by construction of more and more effective dikes, having seaward slopes covered by revetments. Shore stability is now better controlled. This allows to reduce the mean shoreline retreat to few metres per year (while it amounted to 5–30 m in the first half of the last century). Thus, decrease of the erosion rate has not resulted from

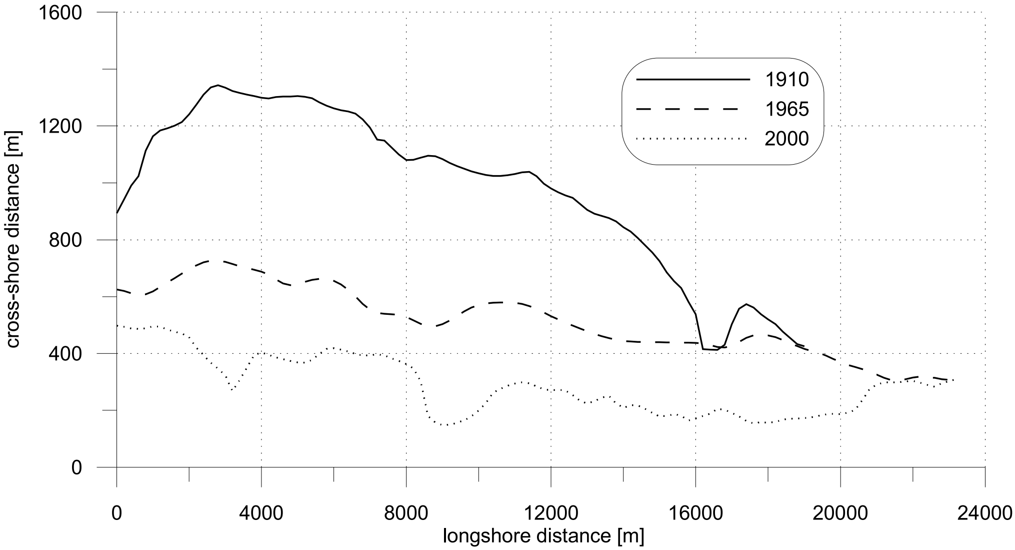

Fig. 15. Long-term shoreline evolution at Hai Hau

stabilisation of natural coastal processes, but from technical intervention on many coastal segments at Hai Hau beach.

A few previous studies pointed out the existing intensive sediment transport in longshore and cross-shore directions. Pruszak et al (2002) stated that the material originating from the Red River system was very mobile. About 70% of the discharged material (mainly clayey) remains suspended, passes the inter-tidal plain and moves offshore where it is subject to sedimentation (down to depths of 30 m). The severe shoreline erosion suggests existence of a significant sediment movement (longshore and cross-shore transport). Recent investigations in 2005 and 2006 reveal that the resultant annual longshore sediment transport is directed southwards, and its net rate amounts to about 150 000 m^3/year. This quantity mainly comprises the amounts of sediment eroded from land and neighbouring underwater parts of the nearshore zone.

4. Discussion

The comparison of coasts representative for two different geographic zones (subtropical region and temperate climate) shows that their behaviour and features much depend on specific climatic conditions and associated environmental features. In the conditions of temperate climate (the Baltic Sea), wind waves and storm surge are of key significance in the coastal zone. Additionally, negative temperatures and related ice phenomena play an important role. Ice on the shoreline makes it more vulnerable to wave impact and erosion. It should be noted that the most frequent and severe storms usually take place in winter and thus can often be correlated with the nearshore ice phenomena (Pruszak et al 2008). In subtropical regions, monsoons with incidental typhoons play a key role in seasonal scale. The impact of even a single typhoon can totally change the existing, relatively stable, morphological coastal system.

It appears that the locations of the considered sites create some differences in coastal hydrodynamic and lithodynamic patterns, which in turn result in specific morphodynamic processes and require different activities while protecting the shore against erosion and flooding.

The observed site-specific physical phenomena and parameters specify the basic differences between the two regions. The major qualitative and quantitative results of the comparison of the sites are summarised in Table 2.

The comparative analysis of the sites yields a fundamental conclusion that the meteorological conditions and related wave climate constitute a major difference between the considered coastal areas. In particular, typhoons in the Gulf of Tonkin are source to enormous hydrodynamic impact which is never present in the Baltic Sea or other similar semi-closed seas. Secondly, tidal effects of the South China Sea seem to be important, especially when superimposed on the storm surges. For coasts located in the region of temperate climate, a crucial role in nearshore morphodynamics is played by wind-generated storms and ice-snowy winter conditions.

It seems that sediment grain size is another important factor. In many tropical and subtropical regions, river-borne aleuritic silt with clay and organic materials are the main components of sediment. The material is much finer at Hai Hau than in the case of Lubiatowo. According to Pruszak et al (2002), grain diameters in the Red River Delta, including the province of Hai Hau, vary from 0.001 to 0.25 mm, with the median grain size d_{50} = 0.09 mm. The sediment consists of non-cohesive matter in 20% only. Hence, the features of sediments are the major factor reflecting the difference between the coasts located in the considered regions. It should be noted that the Lubiatowo sediment is not only coarser but consists of almost purely sandy material. Certainly, this is partly because of climatic conditions in which less organic matter is produced. It should be added that tropical and subtropical regions are dominated by chemical weathering and therefore produce a lot of fine sediment that is discharged by rivers into the sea.

The sea level rise (SLR) phenomenon is not new, and a natural rate of sea level rise of about 0.2 m per 100 years is presently being experienced. Due to accumulated man-made “greenhouse” gases in the atmosphere and the depletion of the ozone layer, climate change effects are expected to take place, which would cause global warming and an accelerated rate of sea level rise over the coming century. By the latest predictions, the accelerated rate of sea level rise will be between 0.3 m and 1 m per 100 years, with the most probable value lying between 0.5–0.6 m/100 yr, see (Pruszak and Zawadzka 2005). The above forecasts require adequate adaptation measures due to increased coastal vulnerability to erosion and

Table 2. Summarised comparison of Site I and Site II

Feature	**Lubiatowo & Hel Peninsula**	**Hai Hau**
surveyed length of the coast [km]	36 (total for two segments)	25
approx. offshore stretch of surveyed coast [km]	1.0 (3.5–4.5 – offshore wave buoy)	1–3
mean annual temperature [C]	7.5	ca. 20
mean nearshore water salinity [PSU]	7	20–32
mean annual rainfall [mm]	650	1740
other key (specific) meteorological and hydrological effects	seasonal moderate rainfalls, ice phenomena, no tides, wind-driven storm surges up to 1.8 m, wind waves and currents	seasonal heavy rainfalls, diurnal tide (with a range of 4 m in the north to 2 m in the south Gulf of Tonkin) plus tidal currents (0.3–1.2 m/s), summer (wet) and winter (dry) monsoons, typhoons, storm surges up to 3 m, waves
maximum wind speed (averaged / gusts) [m/s]	20 / 35–40	35 / 50–80
maximum offshore wave height $H_{\max}$ [m]	7.6	15–20
maximum significant wave height $(H_s)_{\max}$ [m]	4.7	9.7
maximum longshore current velocity [m/s]	1.6 (wave driven)	1.2 (wave-driven superimposed on tidal)
maximum cross-shore current velocity [m/s]	0.4 (directed offshore)	0.4–0.6 (wave-driven superimposed on tidal)
local geology	influence of the last glacial period – coastal sections composed of Pleistocene sediments	young alluvial muddy bodies nourished by river sediment
sediment type, median grain diameter d_{50} [mm]	fine sand, 0.18–0.25	clayey sand, 0.1 (on coast far beyond river mouths); ~ 0.09 and less (clay, organic) in the river and estuary
maximum grain diameter [mm]	0.4 (locally up to 1)	0.25
mean annual longshore sediment transport rate [m^3]	70 000–100 000	100 000–200 000
mean bottom slope	0.01–0.02	0.002–0.01
no. of bars	2–5	0 (in some profiles 1)
emerged beach width [m]	15–70	0–40
extreme shoreline displacement in [m/year]	25 (migration)	30 (erosion)
erosive/accumulative trends	no long-term trend at Lubiatowo, erosion at Hel Peninsula	long-term erosion, locally severe
main applied shore protection measures	groins, beach fills, artificial dunes (at Hel Peninsula only)	sea dikes
other morphological and morphodynamic features	wood-overgrown dunes, grass-overgrown dunes, dune toe protected by fascine fences	low-lying (locally densely inhabited) areas behind dikes
seasonality of processes	variability during a year	distinct annual two-directionality: winter "north" monsoon vs. summer "south" monsoon
sea-level rise [mm/year]	1.7–2.0 (averaged for 1951–1985)	2.24 mm (averaged for 1957–1990)
geological subsidence [mm/year]	very small (below 1)	very limited (below 3)

flooding. Irrespective of the climatic zone, this fact is of great importance in the light of actually observed accelerated sea level rise. Coasts built of fine sediments, located in tidal regions, and subject to typhoons, like Hai Hau beach, seem to be particularly threatened.

In sub-tropical regions, large river mouths and deltas, affecting nearshore hydro- and morphodynamics of the coast, are of key importance. At such locations, sediments (mostly very fine) are moved far offshore and are deposited, forming vast shallows and other forms which significantly alter coastal bathymetry. The Red River delta and its large alluvial fan at the Ba Lat mouth is a typical form disturbing nearshore flow of water at the adjacent beach of Hai Hau. In the temperate climate zone, impact of a river mouth on coastal changes is somewhat smaller, while the key role is played by storm surges, especially when they occur in close succession. On the other hand, ice appearing at a shoreline in winter is a natural factor which distinctly mitigates coastal erosion.

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